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by

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FOREWORD

This is one of a series of Engineering Monographs published by the British Broadcasting Corporation. About six are produced every year, each dealing with a technical subject within the field of television and sound broadcasting. Each Monograph describes work that has been done by the Engineering Division of the BBC and includes, where appropriate, a survey of earlier work on the same subject. From time to time the series may include selected reprints of articles by BBC authors that have appeared in technical journals. Papers dealing with general engineering developments in broadcasting may also be included occasionally.

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CONTENTS

PREVIOUS ISSUES IN THIS SERIES

THE ACOUSTIC DESIGN AND PERFORMANCE OF A NEW FREE-FIELD SOUND MEASUREMENT ROOM

SUMMARY

This monograph sets forth the various requirements laid down in the design of a new free-field room at the BBC Engineering Research Department. Experiments leading to the choice of acoustic absorbent are described and some details given of the building and associated technical equipment. The results of tests on the completed room are given; the frequency range over which free-field conditions can be obtained depends to some extent on the direction of propagation, but in favourable circumstances extends below 50 c/s.

1. Introduction

For the detailed study of electro-acoustic transducers, and for subjective experiments in which an accurately specifiable sound field has to be produced, it is necessary to avoid reflexion of sound from the walls, floor, or ceiling of the test room. It is usually necessary also to reduce extraneous sounds to a very low level. These two requirements can in principle be satisfied by a so-called 'free-field room', in which all surfaces are covered to a considerable depth with acoustic absorbent material, while the structure itself is designed to exclude sound. In practice, however, the approach to the ideal condition of free-field sound propagation with no extraneous noise is limited by economic factors, and a compromise has to be arrived at by taking into account the purpose for which the room is required. This monograph describes the design of a new free-field room at Kingswood Warren, Tadworth, to meet the needs of the BBC Research Department Electro-Acoustics Group. Of the various technical operations for which the new room was intended, the following make the greatest demands on the available space: sound insulation studies involving the measurement of radiation from large sheets of material; measurement of the free-field characteristics of microphone or loudspeaker arrays designed for long-range working; investigations into stereophonic reproduction or other aspects of directional hearing, for which widely spaced sound sources are required. With these requirements in mind, the dimensions of the working space remaining after the introduction of the necessary acoustic absorbent material were fixed at 20 ft by 16 ft by 10 ft high (6·1 m by 4·9 m by 3 m). A working floor offering as little obstruction to sound as possible had to be provided to give easy access to the operating area. Consideration was given to the use of a permanent floor of highly tensioned nylon mesh, such as is fitted in some free-field rooms, but this arrangement was eventually rejected in favour of a rigid floor of steel grids, divided into a large number of removable sections carried on stanchions. The working floor had to be mounted at such a height that any apparatus placed at a point mid-way between the true floor and the ceiling of the room would be in a convenient position for a standing operator. To facilitate the movement of heavy equipment in and out of the room, it was essential that the working floor should be at ground level; to meet this requirement, the room had to be sunk into the ground to a depth of 6 ft (1·8 m).

Since many of the investigations to be carried out in the room were concerned with the high-quality reproduction of music, it was necessary that a good approximation to free-field conditions be maintained over the complete audio-frequency range down to 50 c/s; this requirement will be referred to again in Section 3.

The maximum sound levels to be generated in the room were expected to be of the order of $+120$ dB with reference to 2×10^{-4} dynes/cm^2 and it was not necessary therefore to take precautions, as in the case of some free-field rooms for work involving high-intensity sound, against damage to the acoustic absorbent material through excessive vibration.

Fig. 1 shows the general layout of the free-field room and of the adjacent areas and Fig. 2 a photograph of the interior.

2. Sound Insulation

The most intense noises against which protection is required are those of aircraft flying at a low altitude immediately over the room and of test sounds or programme in an adjacent studio used for experiments in room acoustics. Either noise may be expected to reach a level of $+100$ dB with reference to 2×10^{-4} dynes/cm^2 in octave bands over most of the audible spectrum, with slight reductions below 125 c/s and above 4 kc/s.

As will be seen from Fig 1, the roof and two sides of the room above ground level are exposed to aircraft noise, the front face being protected by an adjoining apparatus room and one side by the acoustics studio, over which is built a photographic studio and office.

If the sound pressure outside is applied to an area A of wall or ceiling, the reduction L in pressure level inside the room is given by

$$L = I - 10 \log_{10} \left(\frac{1}{4} + \frac{A}{R}\right) \text{ dB}$$ [1]

where I is the sound-reduction index (S.R.I.) of the wall or ceiling in dB and R is the 'room constant' given by $S\bar{\alpha}/(1-\bar{\alpha})$ in which S is the total area of the internal surfaces of the room and $\bar{\alpha}$ their mean absorption coefficient.

In a free-field room, $\bar{\alpha}$ must necessarily be nearly unity, so that the term A/R can be neglected; the effective sound insulation of the construction is then increased by 6 dB.

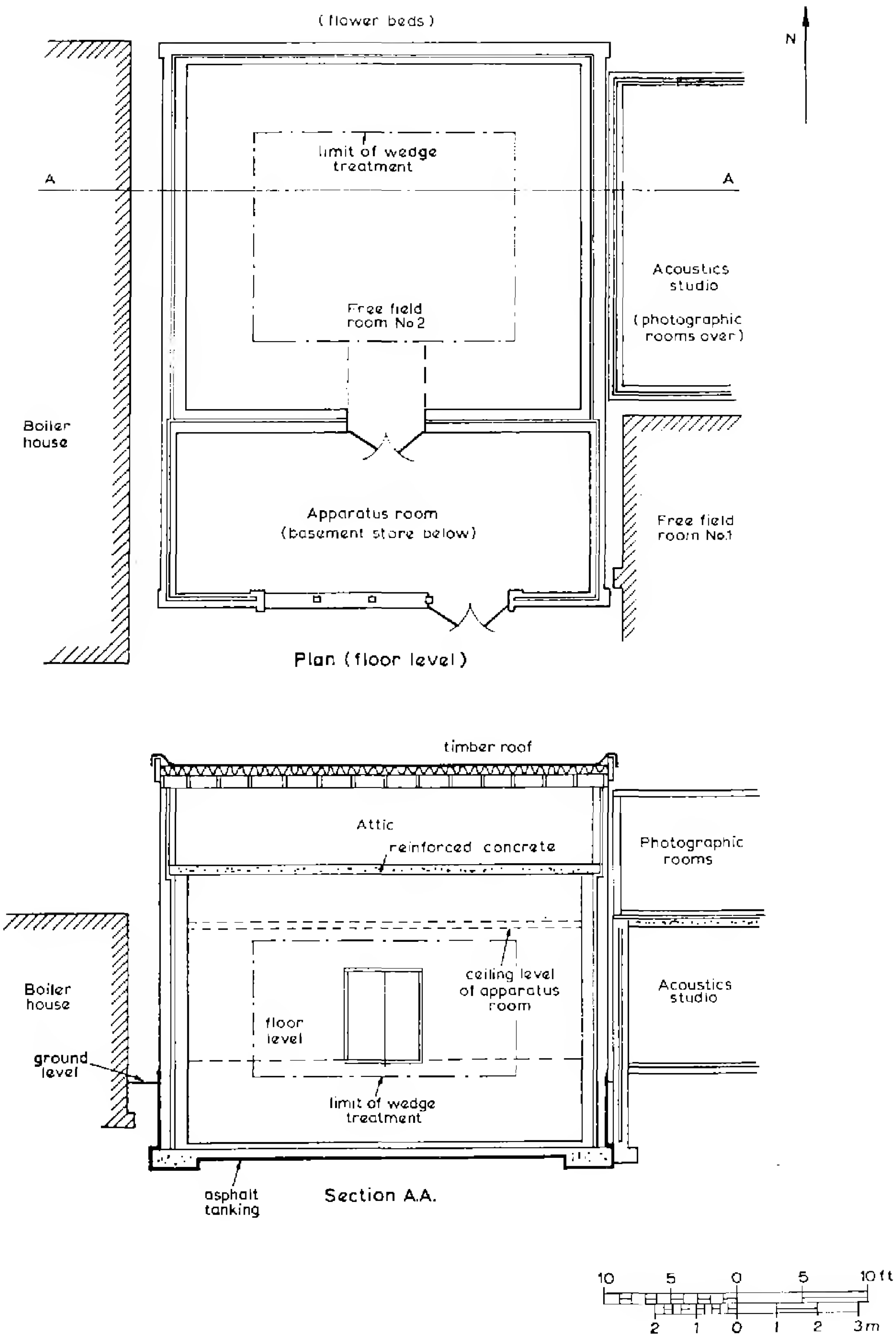


Fig. 1 — General layout of free-field room and adjacent areas

It has been established[2] that the transmission loss through a porous layer adjacent to a solid wall is small or even negative at low frequencies, but roughly additive to that of the wall. On this basis, the loss through the wedges was conservatively estimated as nil at 62 c/s, rising to 34 dB at 8 kc/s.

The requirements for maximum acceptable background noise are based on two types of test. Subjective tests may require the background to be below the threshold of hearing whilst objective measurements of the self-generated noise of microphones, for instance, require a still lower background noise level at low frequencies. A maximum of +15 dB with reference to 2×10^{-4} dynes/cm^2 in any octave band was assumed at frequencies up to 250 c/s above which the threshold of hearing of bands of noise in a diffuse sound field was adopted.

The considerations of external noise, acceptable background noise inside, and necessary corrections as outlined above, finally led to the following requirements for the sound-reduction indices of the ceiling and walls.

Frequency	62	125	250	500	1000	2000	4000	8000	c/s
S.R.I.	68	70	70	70	70	70	69	61	dB

If we consider only the requirements of subjective testing, we obtain instead at low frequencies

Frequency	62	125	250	c/s
S.R.I.	43	61	66	dB

To attain the first set of figures would need a construction which was very uneconomical for middle and high frequencies. To attain the second set of figures would be relatively easy. The construction described in Section 4 represents a compromise between the requirements for subjective tests and objective measurements which may result in occasional interference in some objective measurements at low frequencies.

The isolation of the room from solid-borne impact sounds was also considered. There are no underground sources of vibration or noise, and isolation is therefore required only in respect of footsteps or other impacts at ground level. The room is protected from close approach of footsteps by the apparatus room at the front and flower beds at the back. One side adjoins the studio and the other is flanked by a passage which could be barred if necessary. There is a minimum of 20 ft (6·1 m) of earth between the nearest point of approach and the foundations of the free-field room. This, together with the asphalt tanking over all parts below ground level, was expected to give sufficient protection against footsteps and other sources of ground-borne sound.

Fig. 2 — Interior of free-field room (working floor partially removed)

3. Acoustic Treatment

When the building was first planned it was necessary to decide how much space would be taken up by the sound-absorbent lining. Since the aim of the design was to simulate free-field conditions at all frequencies down to 50 c/s, it was decided that the so-called 'cut-off frequency' at which the reflexion coefficient for normal incidence rises to 10 per cent should be in the region of 45 c/s. From a study of the literature and experience with an existing room built in 1950, it was estimated that the desired result could be achieved by allowing a depth of 5 ft (1·5 m) for acoustic treatment, this figure to include any air space between the absorbent material and the wall. To give the required working space, the dimensions of the bare room were therefore fixed at 30 ft by 26 ft by 20 ft high (9·1 m by 7·9 m by 6·1 m).

From published data on the design of free-field rooms, it is clear that the most effective form of acoustic treatment consists of a series of wedges or pyramids of absorbent material completely covering the walls, floor, and ceiling. There is as yet no satisfactory theory by which the reflexion coefficient of such tapered structures can be calculated from their dimensions and the physical constants of the material employed. Most of the theoretical analyses given in the literature[3–9] are based only on the flow resistance of the material and do not take into account the elastic properties and the dissipation of energy by mechanical hysteresis; in practice, especially with the more elastic materials, it is the mechanical properties rather than the flow resistance which largely determine the sound absorption at low frequencies. However, even when attempts have been made to allow for mechanical movement of the material, the agreement between the predicted and the measured performance of the absorbers is not very good. In the circumstances, therefore, the choice of material and dimensions for the wedge absorbers was made on the basis of experiment.

Most wedge absorbers used in recent years have a cross-section at the base of 8 in. by 8 in. (20 cm by 20 cm). These dimensions are known not to be critical and it was decided therefore not to depart from them. Measurements of reflexion coefficient at normal incidence were made by means of a travelling wave duct having an internal cross-section of 16 in. by 16 in. (40 cm by 40 cm), thus accommodating four wedges.

In practice, a wedge absorber is not tapered over its entire length, the sides being left parallel near the base; moreover, a small air gap between the base of the wedge and the wall of the room usually produces an improvement in performance. Thus, although the base dimensions of the wedge were fixed, three variable dimensions remained—the length of taper, the air gap, and the overall depth taken up by the acoustic treatment; these quantities were varied as required to obtain the optimum performance for each material tested.

As indicated earlier, the lower limit of the useful frequency range of an absorbent material for a free-field room is usually taken as the point at which the reflexion coefficient rises to 10 per cent. To facilitate comparison between different types of sound absorber occupying different amounts of space, some workers have taken as a figure of merit the value of D/λ_0 where λ_0 is the wavelength, in air, of sound at that frequency for which the reflexion coefficient is 10 per cent and D is the overall depth of the acoustic treatment, i.e. the length of the wedge plus the length of the air gap. This procedure, however, produces a figure which decreases when the working frequency range of the absorber increases; to avoid incongruity, the inverse quantity λ_0/D will therefore be used in the present work as a measure of the efficacy of various types of acoustic treatment.

In the free-field rooms built before about 1955, the absorbent materials employed were usually of the glass-fibre or mineral-wool type; these have an unfortunate tendency to shed sharp particles which are a potential danger to the eyes and other delicate surfaces. In recent years, a variety of alternative materials has become available; among those tested for the present purpose were rubberized hair, compressed woodwool, a new resilient type of glass-wool fibre, foamed phenolformaldehyde, and various types of foamed polyurethane.

The best of the fibrous materials, a resin-bonded glass fibre used in the construction of earlier free-field rooms, produced, with optimum wedge dimensions, a figure of 4·3 for λ_0/D; however, this product was no longer on the market and for the nearest available substitute of the same type, λ_0/D was only 3·3.

Attention was then turned to foamed plastic materials, which have the advantage of being free from dust and not easily damaged in handling. A wide variety of plastic foams, both rigid and flexible, was tested, but in every case in which the performance looked promising, the reflexion characteristic was found to be profoundly affected by mechanical resonance in the body of the material. Fig. 3 shows, by way of example, the reflexion characteristic of a polyurethane foam, I,* together with the output of an accelerometer applied to the wedge; for this material, if it were possible to ignore the rise in reflexion coefficient in the region of resonance, λ_0/D would be 3·8. For comparison, the reflexion characteristic of some mineral wool wedges for which λ_0/D is 3·9 is also shown.

Mechanical resonance phenomena in the absorbent material are naturally affected by mechanical constraints, and the influence of these resonances on the reflexion characteristic thus depends a good deal on the method of mounting the wedges. As an example of this, Fig. 4 shows the effect of partially attaching polyurethane ester wedges, II, to the wall by adhesive. The effect of the additional constraint is to reduce the value of λ_0/D from 4·3 to 2·4.

Most foam plastics have very little mechanical hysteresis; their internal resonances are therefore lightly damped and the effects of these are subject to wide variations in manufacture. As an example, curves (*a*) and (*b*) in Fig. 5 show the reflexion characteristics of wedges from two different batches of polyurethane ether foam, III, for which the best value of λ_0/D is 4·5.

* For the sake of brevity and to preserve anonymity, commercial brands of absorbent material are referred to by Roman numerals.

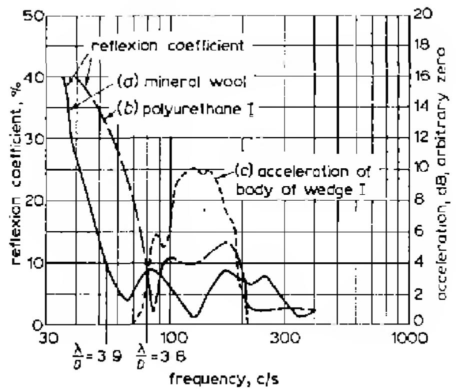


Fig. 3 — Wedges having optimum dimensions

(*a*) Mineral wool. $D = 60$ in. (150 cm)
(*b*) Polyurethane ether I. $D = 44$ in. (112 cm)

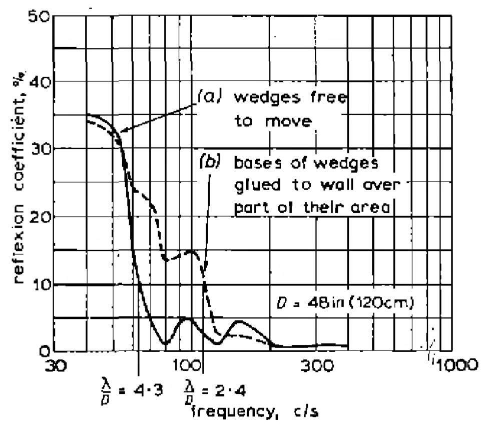


Fig. 4 — Polyurethane ester wedges II for two boundary conditions

$D = 48$ in. (120 cm)

Fortunately, in the course of the investigation a new type of polyurethane ether foam, IV, having an appreciable amount of mechanical hysteresis, became available. Fig. 6 (*a*) shows the reflexion coefficient obtainable with this material, for which λ/D is 4·3; the effect of the increased damping is apparent. Foam IV was found to be sufficiently reproducible in quantity production and was therefore adopted for use in the new free-field room.

In the course of the investigation to determine the optimum material and dimensions of the wedges, consideration was given to the artifice, adopted by some workers,[10] of providing Helmholtz resonators behind the absorbent material, the opening into each resonator being formed by a narrow gap between adjacent wedges. Experiments indicated, however, that even under the most favourable conditions, any increase in absorption obtained by this means was confined to a narrow frequency band and was accompanied by a decrease in absorption at other frequencies. It is thought that some of the effects attributed in the literature to the action of a Helmholtz resonator may in fact have been due to interference between one wave which is reflected from the front of the acoustic treatment and another which has penetrated the material and been reflected from the wall behind.

The dimensions and position of the wedge finally adopted are shown in Fig. 7. An allowance of 6 in. (150 mm) was originally made for the air gap at the rear of the wedge, but with the type of polyurethane foam finally adopted, the optimum gap length was found to be $4\frac{1}{2}$ in. (114 mm). The overall depth of the acoustic treatment is

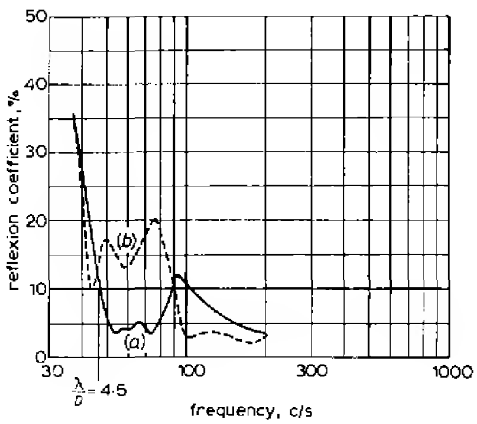


Fig. 5 — Polyurethane ether type III from different batches, (a) and (b)

$D = 60$ in. (150 cm)

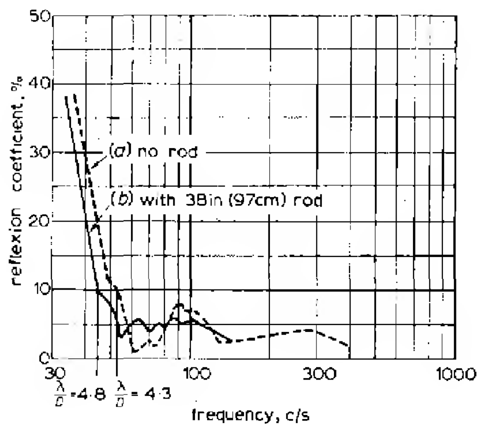


Fig. 6 — Polyurethane ether wedges IV as used for free-field room, with and without steel rod

$D = 60$ in. (150 cm)

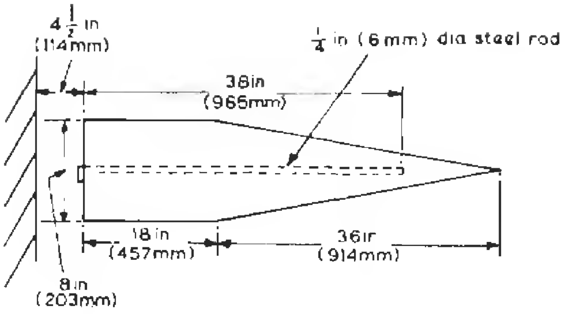


Fig. 7 — Dimensions and position of polyurethane wedge

therefore $1\frac{1}{2}$ in. (40 mm) less than that originally estimated and the working space in the room correspondingly increased. Each wedge is reinforced by a $\frac{1}{4}$ in. (6 mm) diameter steel rod, which is inserted into a hole previously made by a heating element on the end of a probe. It was originally intended to attach these rods to the walls, floor, and ceiling; this method of supporting the wedges had, however, to be abandoned as the mechanical constraint thus introduced adversely affected the sound absorption at low frequencies. Nevertheless, it was found that by leaving the steel rod in place but unattached, the value of λ_0/D could be increased, as shown in Fig. 6 (*b*), to 4·8—a figure which, as far as can be ascertained from the literature, has not been equalled or exceeded by any form of treatment having a cut-off frequency lower than 60 c/s. Experiments made with reinforcing rods of other materials showed that the mass of the rod rather than the stiffness was responsible for the improvement in performance. In the case of wedges used on the floor of the free-field room, the reinforcing rods are divided into sections joined by a spiral spring, forming a flexible element which, in the event of anyone falling on to the acoustic treatment, will fold over without causing injury. As a further safety precaution, the fixed portion of every unused stanchion is covered with a loosely fitting cylindrical cap of sponge rubber; each cap is surmounted by a polyurethane foam wedge 11 in. (280 mm) high to reduce sound reflexion at frequencies for which the flat top presents an appreciable obstacle.

In mounting the wedges in the free-field room, a layer of glass fibre was used to cover any bare surfaces appearing at the junctions of walls, floor, and ceiling.

The main support for the wedges consists of two steel grids, formed by $\frac{1}{4}$ in. (6 mm) rods at 8 in. (200 mm) centres, mounted one behind the other with their meshes in alignment at $5\frac{1}{2}$ in. (140 mm) and $21\frac{1}{2}$ in. (550 mm)

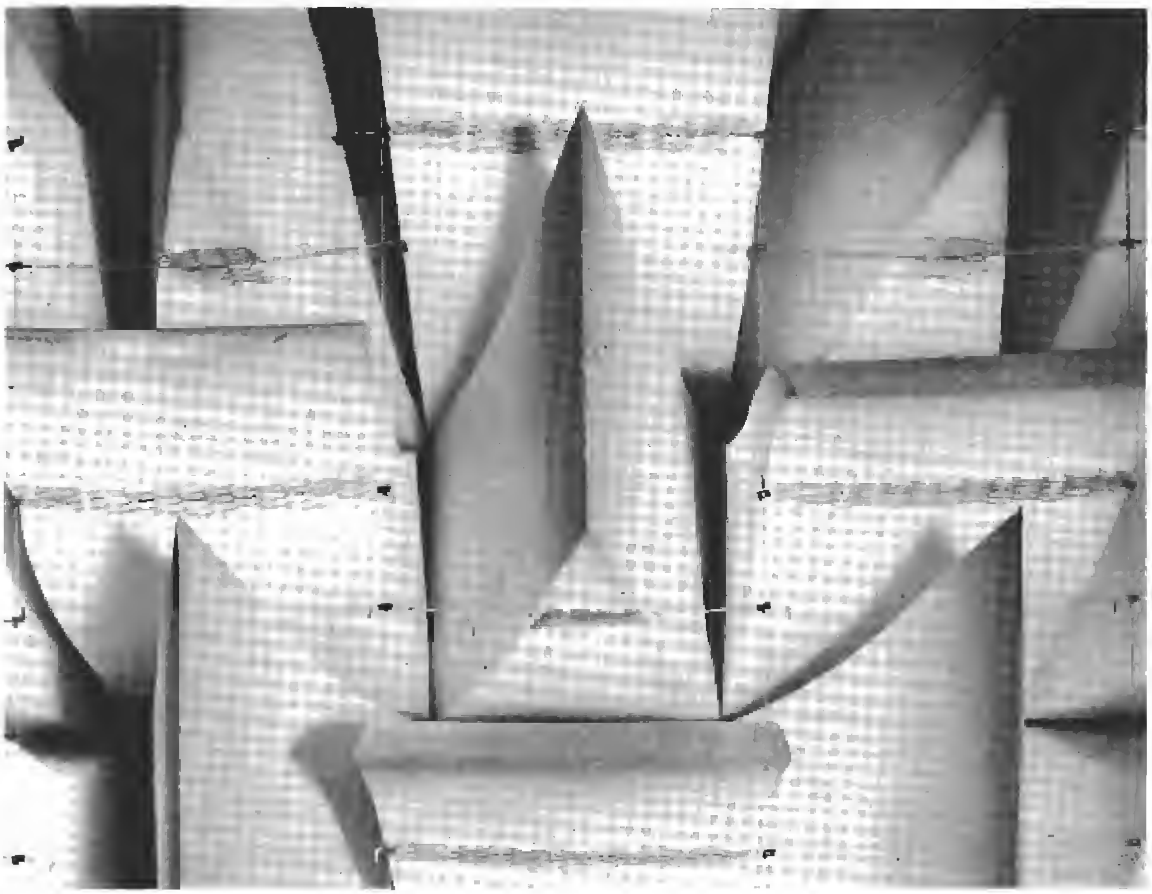


Fig. 8 — Method of supporting wedges to prevent sagging

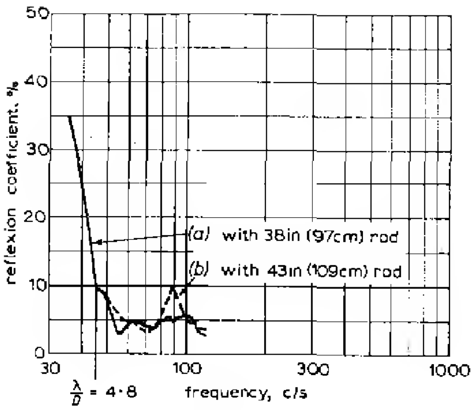


Fig. 9 — Reflexion coefficient of polyurethane ether wedges IV showing effect of increasing length of steel rod

$D = 60$ in. (150 cm)

respectively from the walls, floor, and ceiling. The mesh opening is slightly smaller than the parallel portion of the wedge, so that the latter is gripped firmly; however, it was found necessary to anchor the ceiling wedges by a stiff wire passed transversely through the material near the base.

As the polyurethane foam used is very soft, it was necessary to provide some additional support to prevent excessive sagging of the wedges mounted on the walls; this was achieved, as shown in Fig. 8, by a system of horizontal and vertical wires, small strips of expanded aluminium being interposed to distribute the pressure over the surface of the plastic. The position of the point of support was found to be important; any additional constraint in the neighbourhood of the wedge tip increased the reflexion coefficient in the region of 90 c/s; a similar effect appeared, as shown in Fig. 9, if the length of the steel rod was made too great.

Measurement of the reflexion coefficient of wedges of foam IV was also made at frequencies above 800 c/s, the limit imposed by the onset of transverse resonance modes in the 16 in. by 16 in. (40 cm by 40 cm) test duct. To this end, a smaller duct, of internal cross-section 4 in. by 2 in. (10 cm by 5 cm), was built, which allowed measurements to be made up to 4 kc/s. It was not possible to accommodate a complete wedge in this duct, but a sample was taken from the centre of the wedge, including the tip. The results thus obtained have been combined with the data from Fig. 6 (*b*) to give the overall curve in Fig. 10.

To give some idea of the degree of reflexion to be expected when the sound approaches a bank of wedges at nearly grazing incidence, the tests above 800 c/s were repeated using sections of a wedge arranged with their side surface normal to the direction of sound incidence. The reflexion coefficient at frequencies up to 2·5 kc/s was less than 8 per cent and fell at higher frequencies, as shown in Fig. 11.

Because of the predominant part played by mechanical resonance phenomena in determining the reflexion coefficient of the wedges, it was not possible to check the consistency of the material in production by tests on a small specimen; it was therefore necessary to have a number of full-sized wedges cut from each batch as samples. These samples, amounting to about 2 per cent of the material produced, were tested for reflexion coefficient in the critical frequency range below 200 c/s; in the event of the results falling outside tolerance in this respect (fortunately an infrequent occurrence) the manufacturer was able to utilize the batch for other purposes.

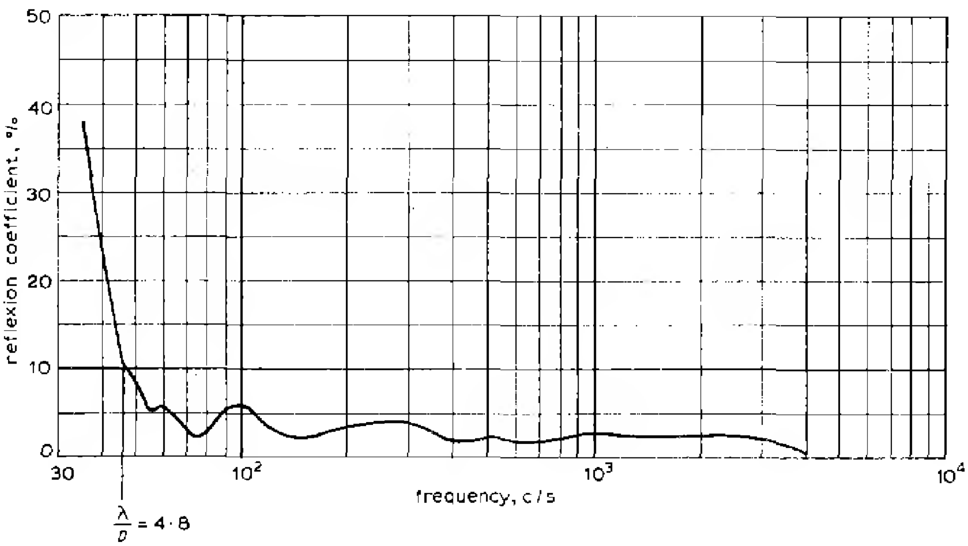


Fig. 10 — Typical reflexion coefficient of polyurethane ether wedges IV as used for free-field room

$D = 60$ in. (150 cm)

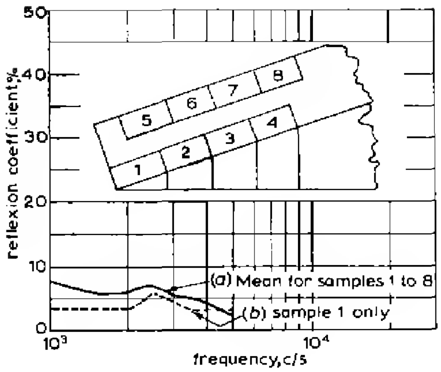


Fig. 11 — *Reflexion coefficient from side of polyurethane ether wedge IV at high frequencies*

Fig. 12 shows the spread of the results obtained with 120 sample wedges, tested in groups of four.

The price of the polyurethane wedges of the type employed in the present room was 20s. 6d. each; the only other material available giving comparable results appears to be a German mineral wool costing about four times this price. It may be noted that one of the types of polyurethane wedge which initially gave promising results, but had to be abandoned because the material was not reproducible, would have cost only about 17s. 6d. The framework holding the wedges in position was made from a standard form of steel mesh employed for reinforcing concrete, the cost being only 1s. per wedge. The 38 in. (0·96 m) rods inserted in the wedges, together with the tip supports, cost an additional 1s. per wedge.

The total number of wedges employed was 5,192. The construction time for the framework and for the wedge supports and the installation of the wedges amounted to approximately 3,160 hours, i.e. 0·6 hours per wedge. This compares with a figure of 1¼ hours per wedge for a free-field room constructed elsewhere in 1947.

4. Structure

For reasons given elsewhere in this monograph, the floor of the room was sunk to a depth of 6 ft (1·8 m). The S wall is protected from aircraft noise by the apparatus room and the space above it and the E wall by the studio, though this is itself a source of noise. The W wall is shielded by the boiler-house. The only completely exposed wall, the N wall, has a height of 14 ft (4·3 m) above ground level and a length of 28 ft (8·5 m). The recommended wall construction was two leaves of 9 in. (220 mm) brickwork with a gap of 8 in. (200 mm) between them. For the roof, 8 in. (200 mm) of concrete was recommended with a working space above roofed with 1 in. (25 mm) of timber or its equivalent in sound insulation. In the final design the roof space was made approximately 6 ft (1·8 m) high and was closed by 2 in. (50 mm) Stramit. For structural reasons and to economize in space, the cavity in the walls was reduced to 3 in. (75 mm). The roof insulation was expected to be adequate but the walls would fall short of the desired insulation even having regard to the relatively small exposed area. It was argued, however, that the thickness of the exposed wall could be increased without difficulty at a later date if it were found to be inadequate.

The inner shell of the free-field room is entirely isolated by the cavity from the outer walls, apart from having a common heavy foundation and compliant fillings round the door frames and in the attic above. The reinforced concrete roof is 9 in. (220 mm) thick and supported by integral rolled steel joists resting entirely on the inner walls. Above this the walls are of two 4½ in. (110 mm) leaves with a 2 in. (50 mm) cavity connected by flexible wall-ties consisting of two galvanized iron strips moulded into a block of cold-cured latex rubber. This construction is also used for the walls of the apparatus room and the storage space above.

It was not considered necessary to extend the outer 9 in. (220 mm) leaf of the S wall of the free-field room above the ceiling of the apparatus room. This ceiling lies approximately 4 ft (1·2 m) below the main ceiling slab of the free-field room, but the storage space is entirely protected by other walls from external sounds. The cavity which therefore appears along one edge of the floor of the storage space was closed with strips of expanded polystyrene lightly wedged into place, largely to prevent small objects from falling into and bridging the cavity.

Protection from test sounds generated in the studio is provided by the two leaves of 9 in. (220 mm) brickwork of the free-field room together with two 4½ in. (110 mm) leaves making up the studio wall. The measured sound reduction index of the combination is 70 dB at 62 c/s, rising with frequency, and is therefore adequate.

The sound reduction from behind through the double 9 in. (220 mm) wall was 64 dB up to 200 c/s with the room complete, rising to 90 dB at 500 c/s. Both these measured results are satisfactory except those through the back wall at the lowest frequencies.

It has not been possible at the time of writing to measure the sound reduction through the roof which is expected to be greater than either of the above.

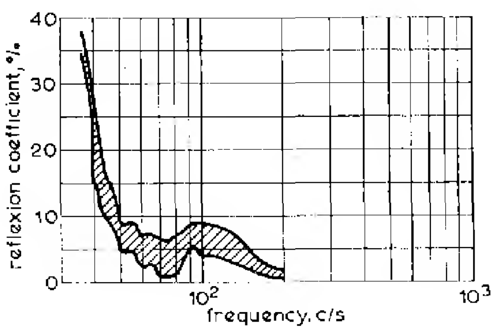


Fig. 12 — *Reflexion coefficient of polyurethane ether wedges IV, showing spread for* 120 *samples tested in groups of four*

5. Technical Equipment

The only piece of technical equipment permanently installed in the free-field room is a 2 in. (50 mm) diameter vertical shaft which projects through a hole in the ceiling and is used to support microphones, or loudspeakers up to 1 cwt (50 kg) in weight. This shaft can be rotated by remote control to facilitate the measurement of polar response characteristics. The polar characteristics of a loudspeaker are normally measured by a microphone mounted on a horizontal boom attached to the lower end of the shaft. The error in rotational position does not exceed $\pm\frac{1}{4}°$ when a 2 lb (1 kg) microphone is carried at a radius of 5 ft (1·5 m) —the worst condition to be expected in practice.

To obviate the necessity for trailing leads, a multicore cable for a standard capacitor microphone together with two screened pairs for the connection of other equipment are brought down inside the shaft and terminated in appropriate connectors.

The lower end of the shaft must be capable of being brought to within 5 ft 4 in. (1·6 m) of the floor so as to be within comfortable reach of all operating personnel. On the other hand, in order to clear the working area of the room the shaft has to be retracted to within 6 in. (150 mm) of the ceiling wedge tips; to meet these requirements, a vertical travel of 3 ft 2 in. (0·97 m) is necessary. The vertical position of the shaft is regulated by a motor drive remotely controlled by a small key switch on an extension lead. To facilitate accurate vertical positioning, the shaft moves at a low speed when first switched on but changes to a higher speed automatically after a few seconds, thus saving time where a large movement is needed.

The equipment for raising, lowering, and rotating the shaft is mounted in a frame resting on two girders which support the ceiling. The complete assembly, shown in Fig. 13, can be transferred to any one of three positions, for which holes in the ceiling are provided.

As a sound source for use in microphone testing, the special loudspeaker shown in Fig. 14 is provided; the enclosure is designed to present the smallest possible frontal area to reduce re-reflexion of any sound reflected back to it by the microphone. The axial frequency characteristic of the loudspeaker is uniform within $\pm$ 2·5 dB from 40 c/s to

Fig. 13 — Retractable shaft for rotating a microphone or loudspeaker; view from above free-field room

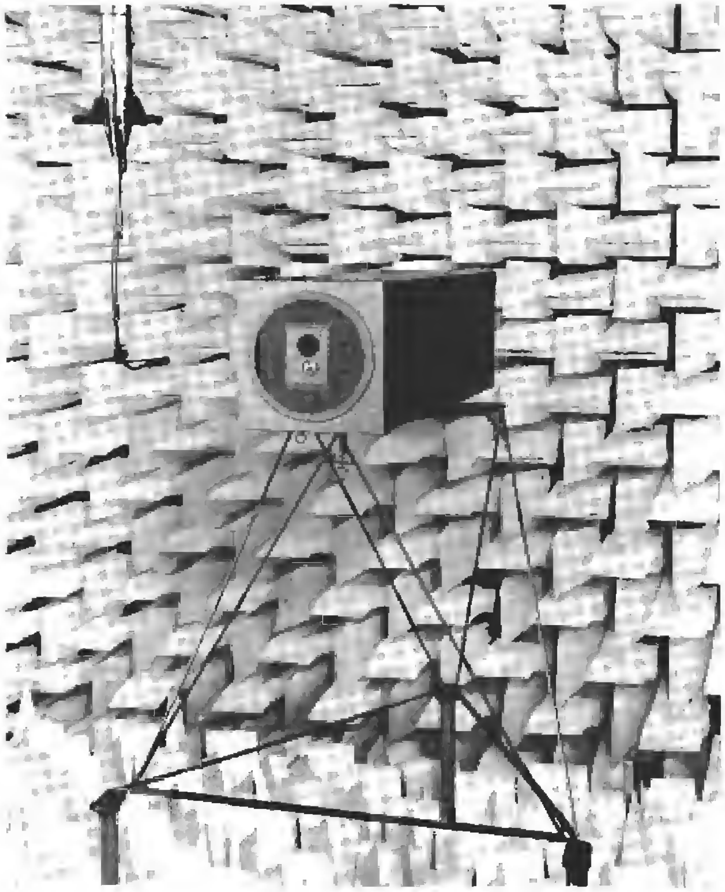


Fig. 14 — Three-unit loudspeaker used as sound source in microphone testing

18 kc/s; this frequency characteristic is achieved by dividing the frequency band into three parts, each dealt with by an appropriate unit. The loudspeaker is carried by a light stand, designed to be acoustically inconspicuous, by means of which it may be supported by the grid floor or by the floor stanchions in one of a number of fixed positions.

The electronic measuring equipment associated with the free-field room is bay-mounted in the adjoining apparatus room. In addition to the usual facilities for continuous tracing of transducer frequency characteristics, provision is made for synchronizing the curve tracing equipment with the rotatable shaft in the free-field room for continuous plotting of polar response characteristics. The equipment also includes an interrupter and synchronized oscilloscope display for transient response measurements.

6. Acoustic Tests

6.1 *Experimental Details*

Several methods of determining how nearly a free-field room approximates to free space have been suggested in the literature.

In one of the procedures recommended in B.S.I. Specification No. 2498:1954, which is concerned with the testing of loudspeakers, 'a microphone and loudspeaker are set up in the room, separated as for taking the frequency characteristic of the loudspeaker, but fixed together so that the combination of microphone and loudspeaker can be moved to different parts of the room without altering their relative positions. The overall frequency characteristics of the combination should be taken for at least four asymmetrical positions in the room so chosen that the microphone positions are at least a quarter wavelength apart at the lowest frequency at which the room is to be used. The degree of approximation to free-space conditions for the particular position of the microphone in relation to the loudspeaker can be estimated from the maximum differences between the frequency characteristics at the different positions.'

The above procedure is open to the objection that at low frequencies the wavelength of sound may be comparable with or greater than the distance between the parallel absorbing surfaces in the room; under these conditions the room acts as a lined duct[11] in which the rate of attenuation of sound pressure with distance exceeds the inverse distance law which applies to free-field conditions. In the test described, this excess attenuation takes the form of a bass cut which is constant and does not therefore appear in the result.

In another method,[12] a loudspeaker and microphone

combination is arranged so that it can be rotated about the axis of the loudspeaker and the variation, with angle, in the microphone output noted. The measurement is performed for various distances of the microphone from the loudspeaker and the departure from constant radiated power calculated. However, in practice this method limits the position of the source to the room centre and the measurements to the horizontal plane.

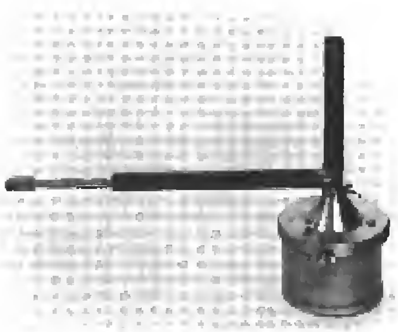
The use of a highly directional microphone has been suggested[13] to determine the level of reflexions from the walls of the room; alternatively, very short pulses of sound may be generated and the level of the reflexions measured. Neither of these tests can, however, be applied at the lower end of the audio-frequency range; in the first case, the necessary directivity is not obtainable while in the second the duration of a cycle is of the same order as the time interval before the arrival of the first reflexion.

The form of test adopted in the present instance is that given as an alternative in the B.S.I. specification already cited. A point source of sound is set up and the pressure-distance relationship explored by means of a movable microphone. Under free-field conditions the sound pressure level from a point source varies inversely with distance and the performance of the room is expressed in terms of the maximum deviation of the sound pressure from this law; tests are carried out along differing paths, for example, along a diagonal or an axis of the room.

It is essential that the loudspeaker employed for the test should approximate closely to a point source, thus giving omnidirectional radiation. If this requirement is not met, optimistic results will be obtained if measurements are made along the acoustic axis of the loudspeaker. In order to simulate a point source at any frequency between 40 c/s and 15 kc/s, it was necessary to use different loudspeakers for different parts of the range. Between 40 c/s and 150 c/s a totally enclosed loudspeaker was employed, having a cabinet of dimensions 30 in. by 18 in. by 12 in. (760 mm by 460 mm by 300 mm) with an aperture 10 in. by 7 in. (250 mm by 180 mm); the sound pressure produced by this loudspeaker was uniform within 1 dB in all directions. Between 200 c/s and 2 kc/s, the horn driver unit shown in Fig. 15 (*a*) was used as the sound source. For the frequency range 2 kc/s to 8 kc/s a still smaller radiator was required, and to this end a driver unit was fitted with a ½ in. (13 mm) diameter extension tube, as shown in Fig. 15 (*b*); to increase the efficiency and reduce effects of non-linearity the device could be tuned to any required frequency by means of a stub let into the side of the main tube and provided with an adjustable piston. At frequencies from 10 kc/s to 15 kc/s a similar device, shown in Fig. 15 (*c*), employing a ¼ in. (6 mm) diameter extension tube without a tuning stub was used.

(*a*)

(*b*)



(*c*)

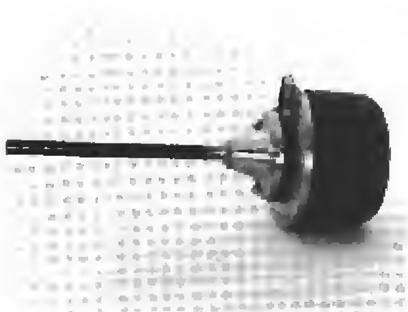


Fig. 15 (*a*) *to* 15 (*c*) — *Sound sources used to give spherical radiation in acoustic tests*

To avoid unwanted discrimination between direct and reflected sound, it is clearly essential in testing for residual reflexions in a free-field room that the microphone as well as the loudspeaker should be omnidirectional. A Beyer moving-coil microphone type M100 was employed. The diameter of the diaphragm is approximately ½ in. (13 mm) and the variation in sensitivity with direction of incidence is not greater than 1 dB up to a frequency of about 5 kc/s. To make the microphone less directional at higher frequencies, recourse was had to a device due to Romanov;[11] this consists of a disk of acoustic resistance material, a little larger in diameter than the microphone, mounted a short distance from the diaphragm. With the Romanov disk the polar response of the Beyer M100 microphone was uniform within 3 dB up to 12 kc/s.

To measure the variation in sound level with distance in the horizontal plane, the microphone was suspended from a light carriage, running on an overhead track, as shown in Fig. 16; the variation in output from the microphone was registered on the chart of a level recorder. The problem of interpreting the resulting curves was eased by employing the following device, which appears to have been first used in this form by Rivin[15] in testing a free-field room in Moscow. The output from the microphone was applied to a compensating potentiometer mounted alongside the track,

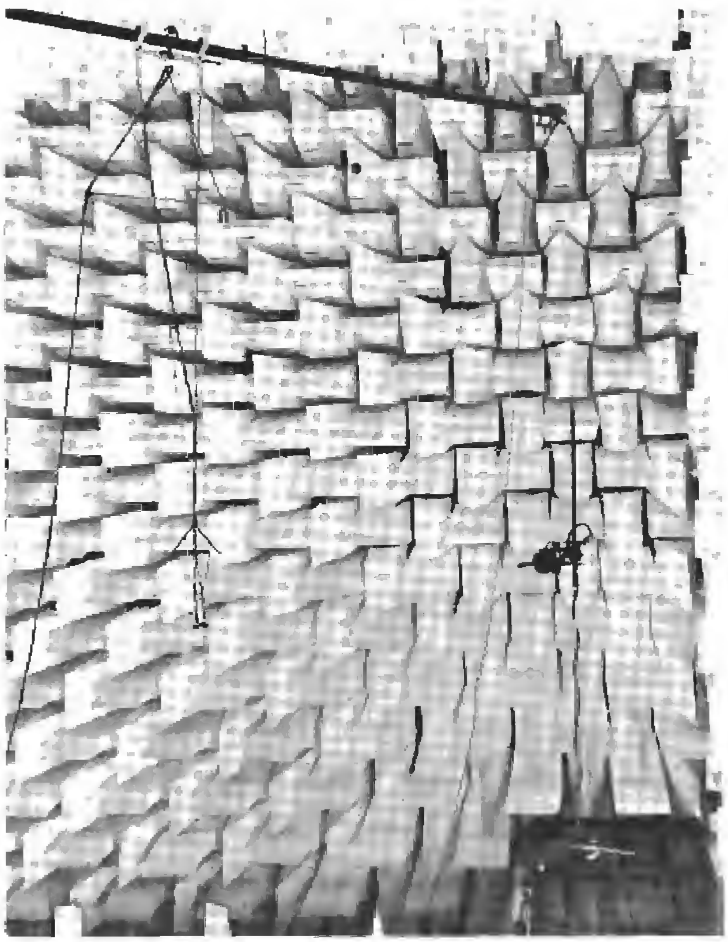


Fig. 16 — Travelling microphone used for acoustic tests

the moving contact being attached to the carriage. The potentiometer was so connected that for a constant input the output from the wiper was proportional to distance d from the source. If the sound level varied exactly as the inverse distance, the output from the potentiometer would be the product $d \times 1/d$ and would therefore remain constant; any deviations from this law are thus indicated on the chart as departures from a constant level and by the use of a suitably expanded scale can be observed with considerable accuracy.

For measurements involving vertical movement, the microphone was attached to an endless cord passing over pulleys at top and bottom, the slide wire being replaced by a multiturn potentiometer coupled to the driving shaft.

Measurements were made over the paths shown in Fig. 17. Paths (*a*), (*b*), and (*c*) were chosen to give the greatest distance possible in the available space along the directions shown, (*a*) along a diagonal and (*b*) along the longer axis of the room; in both these cases the microphone was suspended halfway between the roof and floor treatment. Path (*c*) was similar to that of (*a*) but with the microphone only 1 ft (300 mm) from the tips of the floor wedges. For path (*d*) the sound source was in the room centre—the position in which a loudspeaker under test would be placed; with the source in the centre the sound was incident more nearly at right angles to all the acoustically treated surfaces than for any other location, and the difference between the results for this and other source positions therefore gives an indication of the variation in absorbent properties of the treatment with angle of sound incidence. Path (*e*) was similar to (*a*) but with the grid floor in position. Path (*f*) was in the centre of the room in the vertical plane, with the sound source about 1 ft (300 mm) above the tips of the floor wedges.

6.2 *Results*

Fig. 18, curves (i), (ii), and (iii), gives typical results as they appear on the recorder chart showing the deviations from the inverse distance law as a function of distance. In curve (i), measured at 46 c/s, it will be seen that the deviation is mainly due to the excess attenuation mentioned at the beginning of the section rather than to standing waves in the room; this implies that the wave front will have an additional curvature superimposed on it and some types of measurement in the room will therefore be affected.

In Figs. 19 to 24, the maximum deviation from the in-

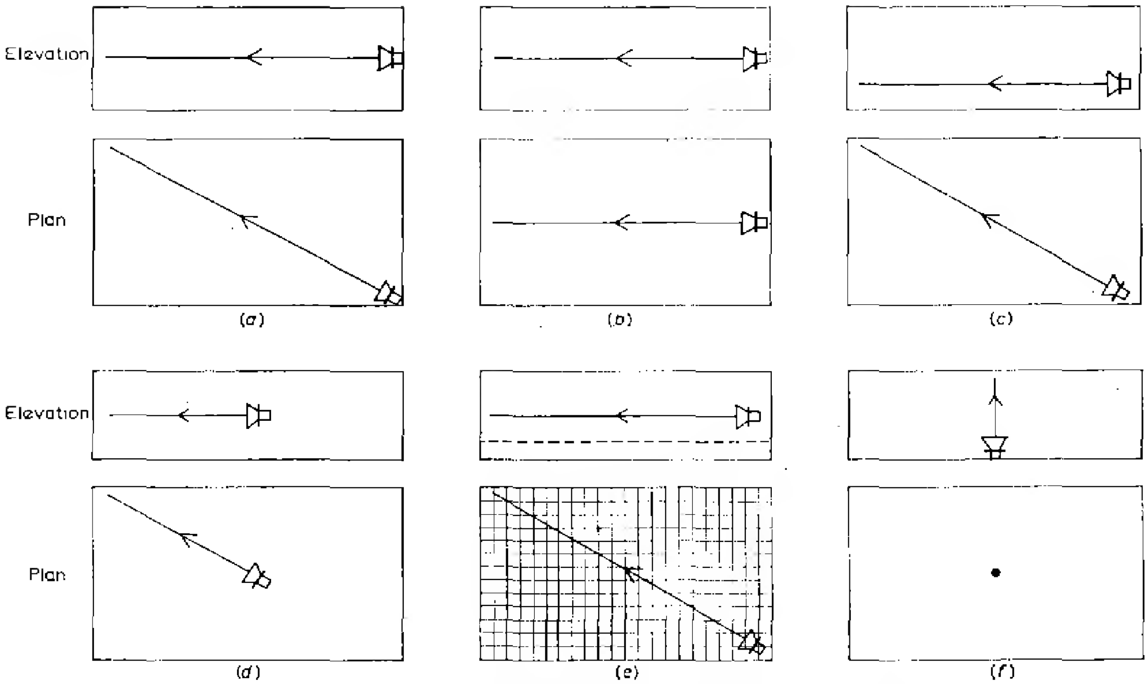


Fig. 17 — Paths along which variations in sound pressure were measured

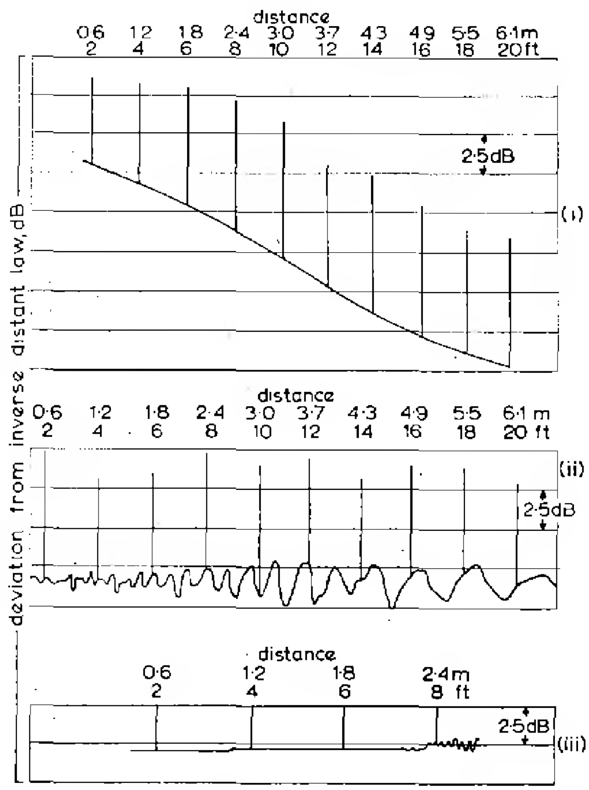


Fig. 18 — Typical examples of recorder chart traces obtained in acoustic tests

(i) 46 c/s, path (*a*)
(ii) 4 kc/s, path (*a*)
(iii) 4 kc/s, path (*f*)

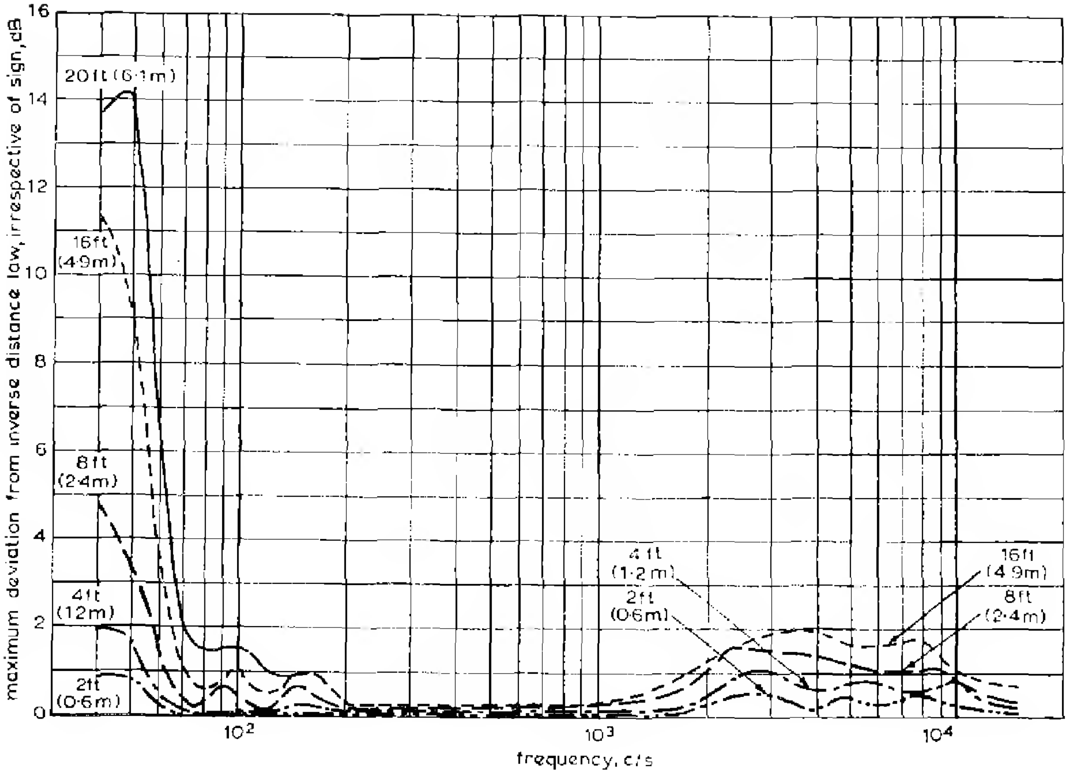


Fig. 19 — Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (a)

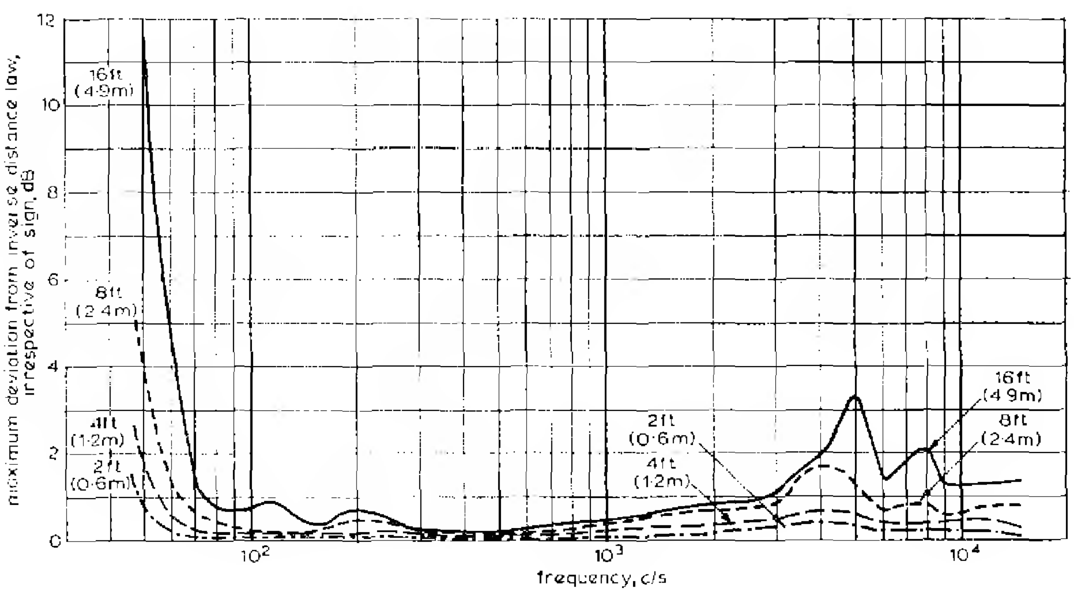


Fig. 20 — Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (b)

verse distance law is plotted, irrespective of sign, as a function of frequency for the different paths shown in Fig. 17. It will be seen from Fig. 19 that up to a distance of 4 ft (1·2 m) from the source on path (*a*) the inverse distance law is followed within about 1 dB over the frequency range 55 c/s to 15 kc/s. In Fig. 20 the departure from the inverse distance law attributable to excess attenuation at low frequencies is slightly less for path (*b*) along the long axis of the room than along the diagonal path (*a*); a similar difference was found in the Moscow room.[15] In Fig. 21 it will be seen that for path (*c*), close to the wedges, in which most of the sound is at almost grazing incidence to the wedges, deviations from the inverse distance law due to excess attenuation are greater than for the other paths, and at large distances from the source can be observed at frequencies up to 3 kc/s. On the other hand, for distances up to 8 ft (2·4 m), deviations at high frequencies due to standing waves are not greater for path (*c*) than for path (*a*) and at 16 ft (4·9 m) only slightly larger; this result is better than that obtained in the Moscow room.[15] In Fig. 22 it can be seen that for path (*d*) the performance at low frequencies is not quite so good as for path (*a*). In Fig. 23 the effect of the floor gratings on the high frequency performance is indicated for path (*e*); under these conditions it is possible to work only 2 ft (0·6 m) from the source if a standing wave ratio of 1 dB is not to be exceeded at 10 kc/s. Fig. 24 shows the results for the vertical path (*f*). It will be noted that for this path the lateral boundaries are remote from the source; as a result the excess attenuation at low frequencies, referred to earlier, is negligible and a close approximation to the inverse distance law is achieved even at 40 c/s.

It will be observed in Figs. 19 and 20 that the deviation from the inverse distance law rises in the 2·5 kc/s to 8 kc/s range. This rise is due to an increase in the amplitude of the standing waves in the room, although no corresponding increase in reflexion factor was found in normal incidence

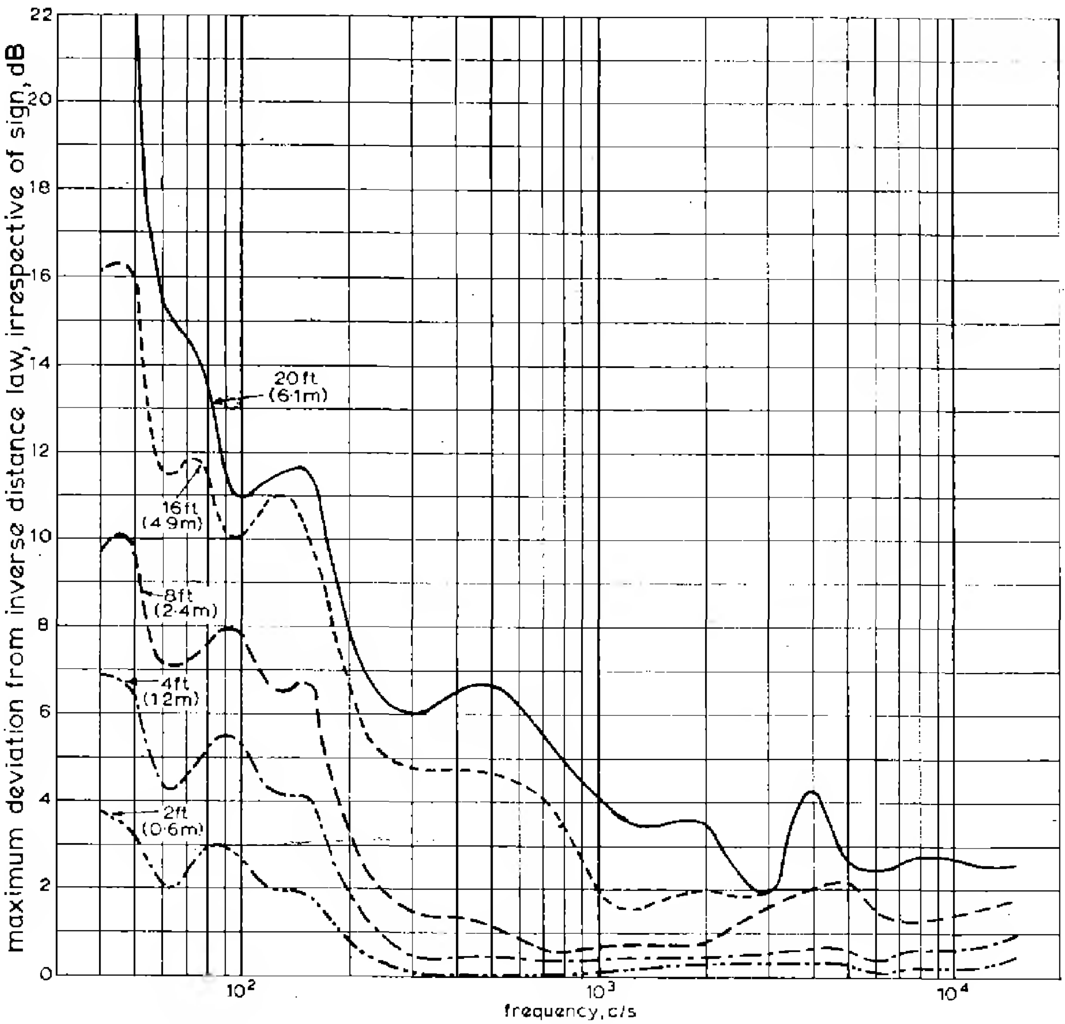


Fig. 21 — Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (c)

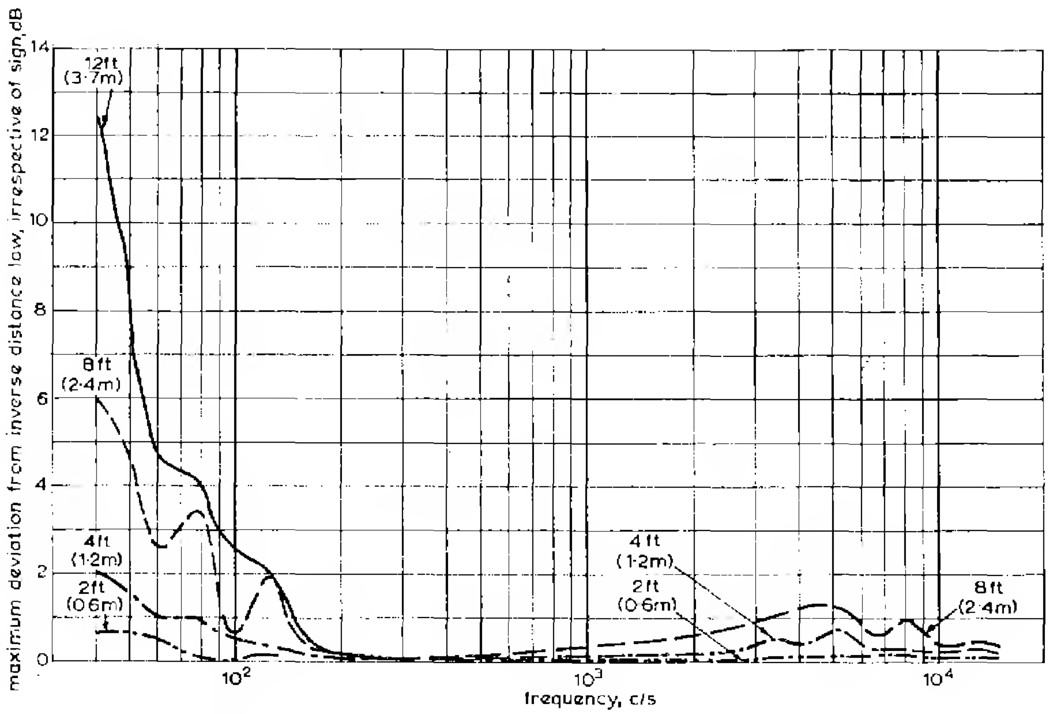


Fig. 22 — Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (d)

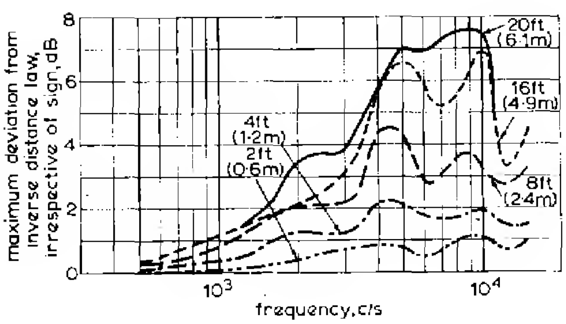


Fig. 23 — Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (e)

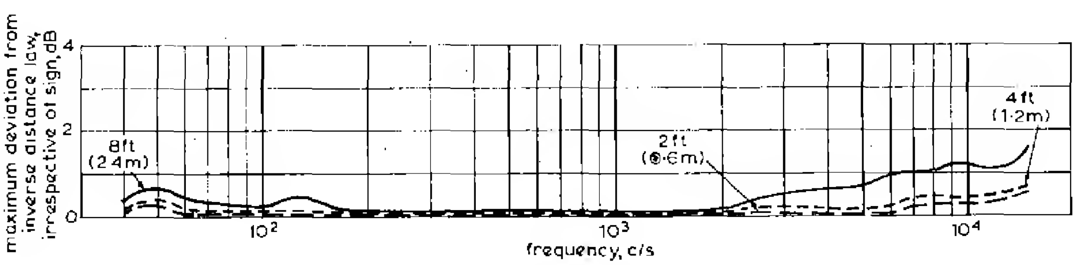


Fig. 24 — Maximum deviation from inverse distance law as a function of frequency, at various distances from sound source: path (f)

measurements on samples of the wedge material, the results of which are given in Fig. 10. It should be noted, however, that at these frequencies sound incident on the sides of the wedges impinges on a flat obstacle of dimensions comparable to or greater than the wavelength; it was calculated from the interference pattern shown in Fig. 18 curve (ii) that the reflexion was taking place from surfaces near the wedge tips on the ceiling and floor and not from the end walls. On the other hand, for path (*f*) the sound is incident much more nearly perpendicular to the treatment and in consequence, as can be seen from Fig. 18 curve (iii), the standing wave effects increase rapidly at the end of the path indicating that the main reflexion comes from the end wall. Other laboratories using wedges of similar width but of different materials have obtained an even greater increase in standing wave ratio in the same frequency range, while in the Moscow room,[15] where the wedges are twice the width of those employed in the present case, an increase in reflexion in the 1 kc/s to 3 kc/s range was reported. It seems likely therefore that reflexion from the flat sides of a large number of wedges is cumulative in certain frequency bands and it appears possible that pyramidal absorbers, a form originally used by Meyer,[16] might be preferable to wedges in this respect. It should be remembered, however, that in practice both sound sources and microphones are normally directional at high frequencies and this will mean that the effect of the room reflexions will be correspondingly less than that shown.

6.3 *Comparison of Calculated with Experimental Results*

It is of interest to compare the above experimental results with those predicted by theory. Olson[17] gives the ratio of reflected to direct energy in a sound field *r* cm from a source as

$$\frac{Er}{Ed} = \frac{16\pi r^2}{S \log_e (1-\alpha)}$$

where α is the effective absorption coefficient derived from the reflexion coefficient in Fig. 10, and S is the area of absorbent. The value to be assigned to S is, however, rather uncertain. At the lowest frequencies sound penetrates the absorbent treatment as far as the wall and the surface area of the untreated room appears to be indicated. On the other hand, it is doubtful whether at frequencies above, say, 200 c/s, the incident sound penetrates much further than the base of the tapered position of the wedges. However, as it is in the lower part of the frequency band that the greatest standing wave ratio exists, the surface area of the bare room has been used in calculating the resulting deviation from the inverse distance law; both the calculated and the measured values are shown in Fig. 25. It will be seen that for a distance of 8 ft (2·4 m) from the sound source the calculated values down to 70 c/s are in good agreement with those measured. As already pointed out, the deviation from the inverse distance law on the curve below this frequency is mainly due, not to standing waves, but to excess attenuation in the room. If this attenuation is ignored and the standing wave ratio estimated from the measurements, the agreement, shown for example by a single point at 56 c/s, is much closer.

Deviations from the inverse distance law were also calculated on the basis of ray theory assuming that only one reflexion would be significant. As before, the reflecting surface was assumed, for the purposes of the calculations, to be at the wall; the results are given in Fig. 26 and are seen to be closely similar to those in Fig. 25. It appears therefore that either approach gives a reasonable indication of the departure from the inverse distance law to be expected in the absence of the excess attenuation at low frequencies.

7. Conclusions

The performance of the new free-field room fulfils the specified requirements. The frequency range over which free-field conditions can be obtained varies with the direction of sound propagation, the lowest cut-off frequency being obtained in the direction parallel to the shortest dimension of the room; it appears that this dimension is a limiting factor in determining the overall performance.

Since the completion of the work described in this monograph, a new mathematical study[18] of the behaviour of wedge absorbers, taking into account the mechanical pro-

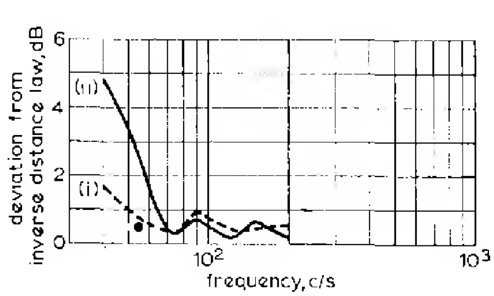


Fig. 25 — Deviation from inverse distance law at 8 ft (2·4 m) from sound source

(i) calculated from reverberation formula
(ii) measured over path (*a*)
● estimated from standing wave ratio (single point)

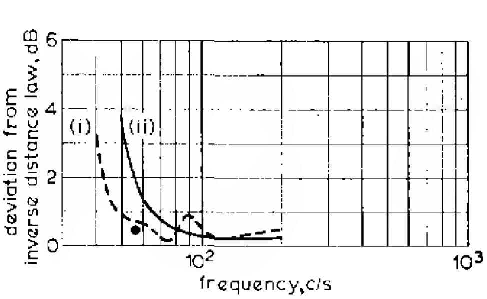


Fig. 26 — Deviation from inverse distance law at 8 ft (2·4 m) from sound source

(i) calculated from ray theory
(ii) measured over path (*b*)
● estimated from standing wave ratio (single point)

perties of the material, has shown that even with cut-off frequencies below 50 c/s, values of λ_0/D approaching 10 can be theoretically envisaged; much more work on materials is, however, required before this possibility can be realized in practice.

8. Acknowledgements

The authors wish to acknowledge the assistance of Mr J.R. Chew, who was responsible for most of the technical equipment referred to in Section 5, and of those members of the Audio-Frequency Section of the BBC Research Department who carried out the various acoustic tests described.

9. References

1. See, for example, Beranek, L. L., **Acoustics**, McGraw-Hill, p. 325, 1954.
2. Beranek, L. L., **Noise Reduction**, McGraw-Hill, p. 370, 1960.
3. Bergman, P. G., **The Wave Equation in a Medium with a Variable Index of Refraction**, J. Acoust. Soc. Am., Vol. 17, No. 4, pp. 329–33, 1946.
4. Rudrick, I., **The Propagation of an Acoustic Wave along a Boundary**, J. Acoust. Soc. Am., Vol. 19, No. 2, pp. 348–56, 1947.
5. Schock, A., **Theory of Linings for Anechoic Rooms**, Physical Society 1948 Summer Symposium of the Acoustics Group, pp. 167–73.
6. Kolar, R. F., **Fields in Imperfect Electromagnetic Anechoic Chambers**, RCA, Rev. Vol. 17, No. 3, pp. 393–409, 1956.
7. Miller, N. B., **Reflections from Gradual Transition Sound Absorbers**, J. Acoust. Soc. Am., Vol. 30, No. 10, pp. 967–73, 1958.
8. Walther, K., **Reflection Factor of Gradual-Transition Absorbers for Electromagnetic and Acoustic Waves**, I.R.E. Trans. Antennas Propag., Vol. AP-8, No. 6, pp. 608–21, 1960.
9. Young, F. J. and B. H., **Impedance of Tapered Structures**, J. Acoust. Soc. Am., Vol. 33, No. 9, pp. 1206–10, 1961.
10. Von Meyer, E., Kurtze, G., Severin, H., and Tamm, K., **Ein neuer grosser reflexionsfreier Raum**, Akust. Beih., Vol. 3, pp. 409–20, 1953.
11. Sabine, H. J., **The Absorption of Noise in Ventilating Ducts**, J. Acoust. Soc. Am., Vol. 12, No. 1, pp. 53–7, 1940.
12. Ellison, A. J., and Miller, B. B., **Design and Construction of the Anechoic Chamber at Queen Mary College**, Proc. Inst. Mech. Eng., Vol. 178, Pt. 1, 2, pp. 53–68, 1963–4.
13. Beranek, L. L., **Design and Construction of Anechoic Sound Chambers**, J. Acoust. Soc. Am., Vol. 18, No. 1, pp. 140–50, 1946.
14. Marshall, R. N., and Romanov, F. F., **A Non-Directional Microphone**, Bell Syst. Tech. J., Vol. 15, No. 3, pp. 405–23, 1936.
15. Rivin, A. N., **An Anechoic Chamber for Acoustical Measurements**, Soviet Phys. Acoust., Vol. 7, No. 3, pp. 258–68, 1962.
16. Meyer, *et al.*, Akust. Z., Vol. 5, p. 352, 1940.
17. Olson, H. F., **Elements of Acoustical Engineering**, Van Nostrand, p. 305, 1940.
18. Head, J. W., **The Design of Gradual-Transition (Wedge) Absorbers for a Free-Field Room**, British Journal of Applied Physics, Vol. 16, No. 7, July 1965.

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